CORRESPONDENCE:
Threats to coastal aquifers

To the Editor — Based on a simple analytical method, Ferguson and Gleeson[1] concluded that coastal aquifers are more vulnerable to groundwater extraction than to sea-level rise (SLR). We argue that this conclusion is premature.

The researchers[1] used Strack's[2] solution to estimate the location of the freshwater/saltwater interface toe in an unconfined coastal aquifer subject both to pumping from a single well and a constant regional groundwater flux from inland. They also compared pumping impacts with those of SLR, except in this case, a constant hydraulic head was assumed at the inland boundary. The inconsistency in the boundary conditions has important implications for the comparison of SLR and pumping impacts. For example, in terms of steady-state toe location, constant flux gives maximum pumping impact and minimum SLR impact; whereas constant head gives maximum SLR impact and minimum pumping impact[3,4].

Werner *et al.*[3] and Lu *et al.*[4] provide the relevant equations and discussion for the different boundary conditions. Let us assume the case[1] of a pumping well located at the centre of an aquifer with a length perpendicular to the coastline of 2 km, a thickness of 30 m, a hydraulic conductivity of 1.6×10^{-5} m s^{-1}, hydraulic gradient of 0.001 and pumping rate of 4.4×10^4 l d^{-1}. This would lead to saltwater intrusion lengths of 162 m and 254 m, using constant head and flux inland boundary conditions, respectively. For the case of SLR, the same aquifer would experience saltwater intrusions of 161 m and 15 m following a SLR of 0.59 m, under constant head and flux inland boundary conditions, respectively.

In reality, inland boundary conditions are likely to fall between the two extremes of fixed flux and fixed head. This is partly owing to topographical controls on water table rise and the water table being impacted by land surface inundation under SLR. The fact that both boundary conditions assume an infinite supply of water at the inland boundary also plays a part. As a result, it is necessary to consider both types of boundary condition in assessing groundwater extraction and SLR. This analysis serves to demonstrate how important the choice of boundary condition is when making an assessment of the relative impacts of groundwater extraction and SLR. It also illustrates the difficulty in drawing generalized conclusions, especially for the cases with a short aquifer length. Furthermore, there are implicit and often unjustified assumptions that catchment boundaries coincide with groundwater basin boundaries[5].

Moreover, Ferguson and Gleeson[1] considered groundwater extraction from a single well, although well fields in coastal aquifers usually have multiple wells[5,6]. In the latter case, drawdown is reduced relative to the same total extraction from a single well, leading to a smaller inland penetration of saltwater intrusion.

Ferguson and Gleeson[1] considered only the location of the interface toe, which is but one of several measures of saltwater intrusion impact[3]. Saltwater volume is a key measureable given that spatial scales of influence and impact vary significantly between SLR and pumping. Considering a 10-km-wide coastline and the same cases as above, volumes of saltwater intrusion through pumping (flux controlled) and SLR (head controlled) are 4.2×10^6 m^3 and 1.9×10^7 m^3, respectively, despite the inland penetration of saltwater intrusion owing to pumping being larger than that caused by SLR. An assessment of saltwater volume will surely show that in many cases, where pumping is localized and not widely distributed, SLR-induced saltwater intrusion across vast lengths of coastline leads to more extensive freshwater storage losses than from pumping.

In summary, the selection of boundary conditions is a key aspect to the comparison between pumping and SLR impacts. Moreover, owing to the different mechanisms of saltwater intrusion induced by groundwater extraction and SLR, we suggest that the assessment of their relative impacts on the vulnerability of a coastal aquifer should consider changes in both toe location and saltwater volume, among other factors. In considering only the toe location, Ferguson and Gleeson's[1] results are biased towards pumping impacts; a comparison of saltwater volume changes would provide a more integrated analysis of saltwater intrusion impacts, given spatial differences in pumping and SLR effects. A more thorough assessment of the distributions of inland boundary conditions required and the various controls on saltwater intrusion need to be investigated further[5] before firm and well-found conclusions regarding the relative importance of SLR and pumping can be made. ❐

References

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Ferguson and Gleeson reply — We appreciate the correspondence of Lu *et al.*[1] on our analysis of coastal aquifer vulnerability[2]. They raise some interesting points of discussion that allow us an opportunity to further explain our analysis. Lu and colleagues' arguments[1] do not substantially change our conclusions[2] regarding the vulnerability of unconfined coastal aquifers (the focus of our study) to sea-level rise (SLR) but are of interest for smaller flow systems.

Lu *et al.* argue that our choice in boundary conditions affects the calculated values of saltwater intrusion. Two terrestrial boundary conditions are generally recognized for groundwater flow in unconfined coastal aquifers: head controlled and recharge or flux controlled[3]. We acknowledge that there is uncertainty about which boundary condition is most appropriate for a particular coastal aquifer. For our analysis, we chose a head-controlled boundary condition that leads to more significant changes in hydraulic gradient for a given rate of SLR[3] when compared with a flux-controlled boundary condition.

Table 1 | Saltwater intrusion as defined by movement of the toe of the saltwater wedge inland in response to pumping at 4.4×10^4 l d^{-1} for constant head (CH) and constant flux (CF) boundaries in 2-km-long coastal aquifers used by Lu *et al.*[1] and 10-km-long coastal aquifers used by Ferguson and Gleeson[2].

2-km-long coastal aquifer				10-km-long coastal aquifer			
Pumping		SLR		Pumping		SLR	
CH	CF	CH	CF	CH	CF	CH	CF
162	254	161	15	256	251	17	15

However, as Lu *et al.* note, we followed the pumping treatment developed by Strack[4] that uses a flux-controlled boundary, which seems inconsistent. Here we expand our analysis to assess the impact of each boundary condition both on pumping and SLR scenarios both in small and large coastal aquifers more rigorously (Table 1).

Our analysis was based on a detailed geomatic analysis of >1,400 coastal watersheds in North America[2]. We use watershed boundaries because many of the coastal water tables in the United States are controlled by topography and in those cases watershed divides generally correspond to groundwater divides[5]. The aquifer length used by Lu *et al.* is not representative of coastal aquifers, at least in North America. The length of the coastal watershed used in their calculation is 2 km, yet <3% of coastal watersheds in North America are ≤2 km. For a 10-km-long flow system, the mean coastal watershed length for North America, the impacts of SLR and pumping are relatively insensitive to the boundary condition (Table 1). We agree that the choice of boundary conditions could have significant implications for shorter flow systems, which are more sensitive to SLR in general.

Lu and colleagues' results are based on a relatively low pumping rate of 4.4×10^4 l d^{-1}, a rate that would supply drinking water to ~80 Americans. This low pumping rate, which is also unrepresentative of coastal watersheds in North America, results in a population density of four people per square kilometre for the aquifer dimensions presented. This is quite low compared with the average US coastal population density of >100 people per square kilometre.

Using these two less-representative parameter values can result in more significant impacts of SLR relative to pumping, depending on the boundary conditions (Table 1). These parameter values are appropriate for some coastal aquifers, but the analysis presented[1] by Lu *et al.* does not represent a typical setting in the contiguous United States. Therefore, the calculations in the correspondence do not impact our primary conclusion that unconfined coastal aquifers are more vulnerable to groundwater extraction than to predicted SLR under a wide range of representative hydrogeological conditions and population densities.

Lu *et al.* also argue that distributing pumping over numerous wells instead of one well reduces the impact of pumping on saltwater intrusion. Distributing pumping over several wells will have a smaller effect on hydraulic head and saltwater intrusion than our analysis, which examined only a single well. Mitigation of some of the impacts of pumping could be accomplished in this manner.

Finally, Lu *et al.* suggest that the volume of intruded saltwater is an another metric for comparing the impact of SLR and pumping. The volume of intruded saltwater may indeed provide insight into the dynamics of saltwater intrusion. However, such estimates are highly sensitive and dependent on the coastline width considered. In the example provided by Lu *et al.*, a 10-km-wide stretch of coastline is considered for an aquifer extending a length of 2 km inland, emphasizing the importance of SLR. Lu *et al.* do not provide any justification for their choice of coastline width. Examining a wide section of coastline with few wells emphasizes the effect of SLR and produces results that are not representative of the situation in the United States. However, the metric proposed by Lu *et al.* may be useful for studies focused on groundwater–surface water interaction or ecological impacts. ❐

References

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CORRESPONDENCE:

Blood product safety

To the Editor — I read with interest Jan Semenza and Dragoslav Domanović's thoughtful discussion of the potential impact of climate change on the European blood supply[1]. The US Food and Drug Agency (FDA) collaborates with others to ensure blood product safety[2].

The FDA has recently co-sponsored public workshops to discuss emerging infectious diseases including 'Data and data needs to advance risk assessment for emerging infectious diseases relevant to blood and blood products' (November 2011) and 'Emerging infectious diseases: Evaluation to implementation for transfusion and transplantation safety public workshop' (May 2010; http://go.nature.com/3ru1G5). The FDA's blood product advisory committee has also considered these topics at various meetings (http://go.nature.com/QD4QXe)

Semenza and Domanović's article sends a message that blood sector stakeholders — blood establishments, consumer and patient groups, health care entities/providers, regulatory agencies and others — should be part of broader discussions about climate change. These organizations should join others in appropriate advocacy efforts, such as those led in the United States by